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<b>(21) International Application Number:</b> PCT/US99/06661  <b>(22) International Filing Date:</b> 26 March 1999 (26.03.99)  <b>(30) Priority Data:</b> 60/079,378                      26 March 1998 (26.03.98)                      US Not furnished                      26 March 1999 (26.03.99)                      US  <b>(71) Applicant (for all designated States except US):</b> DIGITAL OPTICS CORPORATION [US/US]; Suite J, 5900 Northwoods Parkway, Charlotte, NC 28269 (US).  <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> FELDMAN, Michael, R. [US/US]; 3117 Lakewood Edge, Charlotte, NC 28269 (US). KATHMAN, Alan, D. [US/US]; 4700 Lone Tree Lane, Charlotte, NC 28269 (US). WELCH, William, Hudson [US/US]; 735 Foxborough Road, Charlotte, NC 28213 (US).  <b>(74) Agent:</b> MORSE, Susan, S.; Jones, Volentine, Steinberg & Whitt, L.L.P., Suite 150, 12200 Sunrise Valley Drive, Reston, VA 20191 (US).		<b>(81) Designated States:</b> AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>Without international search report and to be republished upon receipt of that report.</i>
<b>(54) Title:</b> INTEGRATED MICRO-OPTICAL SYSTEMS  <b>(57) Abstract</b>  <p>An integrated micro-optical system includes at least two wafers with at least two optical elements provided on respective surfaces of the at least two wafers. An active element having a characteristic which changes in response to an applied field may be integrated on a bottom surface of the wafers. The resulting optical system may present a high numerical aperture. Preferably, one of the optical elements is a refractive element formed in a material having a high index of refraction.</p>		

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## INTEGRATED MICRO-OPTICAL SYSTEMS

### Cross-references to Related Applications

The present application claims priority under 35 U.S.C. §119 to U.S. Provisional Application No. 60/079,378 filed on March 26, 1998, the entire  
5 contents of which are hereby incorporated by reference.

### BACKGROUND OF THE INVENTION

#### Field of the Invention

The present invention is directed to integrating optics on the wafer level  
10 with an active element, particularly for use with magneto-optic heads.

#### Description of Related Art

Magneto-optical heads are used to read current high-density magneto-optic media. In particular, a magnetic coil is used to apply a magnetic field to the media and light is then also delivered to the media to write to the media. The light is also  
15 used to read from the media in accordance with the altered characteristics of the media from the application of the magnetic field and light.

An example of such a configuration is shown in Figure 1. In Figure 1, an optical fiber 8 delivers light to the head. The head includes a slider block 10 which has an objective lens 12 mounted on a side thereof. A mirror 9, also  
20 mounted on the side of the slider block 10, directs light from the optical fiber 8 onto the objective lens 12. A magnetic coil 14, aligned with the lens 12, is also

mounted on the side of the slider block 10. The head sits on top of an air bearing sandwich 16 which is between the head and the media 18. The slider block 10 allows the head to slide across the media 18 and read from or write to the media 18.

5           The height of the slider block 10 is limited, typically to between 500-1500 microns, and is desirably as small as possible. Therefore, the number of lenses which could be mounted on the slider block is also limited. Additionally, alignment of more than one lens on the slider block is difficult. Further, due to the small spot required, the optics or overall optical system of the head need to have  
10   a high numerical aperture, preferably greater than .6. This is difficult to achieve in a single objective lens due to the large sag associated therewith. The overall head is thus difficult to assemble and not readily suited to mass production.

#### SUMMARY OF THE INVENTION

          Therefore, it is an object of the present invention to provide a slider block  
15   having an active element, i.e., an element having a characteristic which changes in response to an applied field, integrated thereon which substantially overcomes one or more of the problems due to the limitations and disadvantages of the related art. Such elements include a magnetic coil, a light source, a detector, etc.

          It is a further object of the present invention to integrate multiple optical  
20   elements and a slider block having the active element integrated thereon as well.

          It is a further object of the present invention to manufacture the objects on a wafer

level, bond a plurality of wafers together and provide the active element on a bottom surface of a bottom wafer.

At least one of the above and other advantages may be realized by providing an integrated micro-optical system including a die formed from more than one wafer bonded together, each wafer having a top surface and a bottom surface, bonded wafers being diced to yield multiple dies and an active element having a characteristic which changes in response to an applied field, integrated on a bottom surface of the die, optical elements being formed on more than one surface of the die.

The active element may be a thin film conductor whose magnetic properties changes when a current is applied thereto. The active element may be integrated as an array of active elements on the bottom wafer before the bonded wafers are diced. The die may be formed from two wafers and optical elements are formed on a top surface and a bottom surface of a top wafer and a top surface of the bottom wafer. The die may include a high numerical aperture optical system.

The bottom wafer of the more than one wafer may have a higher index of refraction than other wafers. There may be no optical elements on a bottom wafer of the die. The bottom surface of the die may further include features for facilitating sliding of the integrated micro-optical system etched thereon. The bottom wafer of the die may have a refractive element formed in a material of high numerical aperture. Metal portions serving as apertures may be integrated on at least on one the surfaces of the die.

A layer of material deposited on the bottom surface of the bottom wafer before the active element is integrated thereon. An optical element may be formed on the bottom surface of the bottom wafer, wherein the layer has a refractive index that is different from the refractive index of the bottom wafer. The layer may be  
5 deposited in accordance with a difference between a desired thickness and a measured thickness.

A monitoring optical system may be formed on each surface of the wafer containing an optical element. The spacing between wafers may be varied in accordance with a difference between a measured thickness of a wafer and a  
10 desired thickness of a wafer.

A top surface of the die may be etched and coated with a reflective coating to direct light onto the optical elements. A further substrate may be mounted on top of the top of the die having a MEMS mirror therein. An insertion point may be provided on the die for receiving an optical fiber therein. The insertion point  
15 may be on a side of the die and the system further includes a reflector for redirecting light output by the fiber.

A refractive element in the die may be a spherical lens and the die further includes a compensating element which compensates for aberrations exhibited by the spherical lens. The compensating element may be on a surface immediately  
20 adjacent the spherical lens. The compensating element may be a diffractive element. The refractive element may be an aspheric lens. The die may include at

least one additional refractive element, all refractive elements of the die being formed in material having a high numerical aperture.

At least one of the above and other advantages may be realized by providing an integrated micro-optical apparatus including a die formed from more than one wafer bonded together, each wafer having a top surface and a bottom surface, bonded wafers being diced to yield multiple die, at least two optical elements being formed on respective surfaces of each die, at least one of the at least two optical elements being a refractive element, a resulting optical system of each die having a high numerical aperture.

10 The refractive element may be a spherical lens and the die further includes a compensating element which compensates for aberrations exhibited by the spherical lens. The compensating element may be on a surface immediately adjacent the spherical lens. The compensating element may be a diffractive element. The refractive element may be an aspheric lens.

15 The die may include at least one additional refractive element, all refractive elements of the die being formed in material having a high numerical aperture. The refractive element may be on a bottom wafer and of a material having a higher refractive index than that of the bottom wafer.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various



changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

### BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed  
5 description given herein below and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

Figure 1 illustrates a configuration of a high-density flying head magneto-optical read/write device;

10 Figure 2A illustrates one configuration for the optics to be used in forming a slider block;

Figure 2B illustrates the spread function of the optical system shown in Figure 2A;

Figure 3A illustrates a second embodiment of the optics for use in sliding  
15 block of the present invention;

Figure 3B illustrates the spread function of the optical system shown in Figure 3A;

Figure 4A illustrates a third embodiment of an optical system to be used in the slider block of the present invention;

20 Figure 4B illustrates the spread function of the optical system shown in Figure 4A;



Figure 5 is a side view of an embodiment of a slider block in accordance with the present invention;

Figure 6 is a side view of another embodiment of a slider block in accordance with the present invention;

5        Figure 7 is a side view of another embodiment of a slider block in accordance with the present invention;

Figure 8A is a side view of another embodiment of a slider block in accordance with the present invention; and

Figure 8B is a bottom view of the embodiment in Figure 8A.

10

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

All of the optical systems shown in Figures 2A-4B provide satisfactory results, i.e., a high numerical aperture with good optical performance. The key element in these optical systems is the distribution of the optical power over multiple available  
15    surfaces. Preferably this distribution is even over the multiple surfaces. Sufficient distribution for the high numerical aperture required is realized over more than one surface. Due to the high numerical aperture required, this distribution of optical power reduces the aberrations from the refractive surfaces and increases the diffractive efficiency of the diffractive surfaces by reducing the deflection angle required from  
20    each surface.

Further, a single refractive surface having a high numerical aperture would be difficult to incorporate on a wafer, since the increased curvature required for affecting

such a refractive surface would result in very thin portions of a typical wafer, leading to concerns about fragility, or would require a thick wafer, which is not desirable in many applications where size is a major constraint. Further, the precise shape control required in the manufacture of a single refractive surface having high NA would  
5 present a significant challenge. Finally, the surfaces having the optical power distributed are easier to manufacture, have better reproducibility, and maintain a better quality wavefront.

In accordance with the present invention, more than one surface may be integrated with an active element such as a magnetic coil by bonding wafers together.  
10 Each wafer surface can have optics integrated thereon photolithographically, either directly or through molding or embossing. Each wafer contains an array of the same optical elements. When more than two surfaces are desired, wafers are bonded together. When the wafers are diced into individually apparatuses, the resulting product is called a die. The side views of Figs. 2A, 3A, and 4A illustrate such dies  
15 which consist of two or three chips bonded together by a bonding material 25.

In the example shown in Figure 2A, a diffractive surface 20 is followed by a refractive surface 22, which is followed by a diffractive surface 24, and then finally a refractive surface 26. In the example shown in Figure 3A, a refractive surface 30 is followed by a diffractive surface 32, which is followed by a refractive surface 34  
20 which is finally followed a diffractive surface 36. In the optical system shown in Figure 4A, a refractive surface 40 is followed by a diffractive surface 42 which is followed by a refractive surface 44 which is followed by a diffractive surface 46,

which is followed by a refractive surface 48 and finally a diffractive surface 50. The corresponding performance of each of these designs is shown in the corresponding intensity spread function of Figs. 2B, 3B, and 4B.

When using spherical refractive elements as shown in Figures 2A, 3A and 4A,  
5 it is convenient to follow these spherical refractive elements with a closely spaced diffractive element to compensate for the attendant spherical aberration. An aspherical refractive does not exhibit such aberrations, so the alternating arrangement of refractives and diffractives will not necessarily be the preferred one.

While the optical elements may be formed using any technique, to achieve the  
10 required high numerical aperture, it is preferable that the refractive lenses remain in photoresist, rather than being transferred to the substrate. It is also preferable that the bottom substrate, i.e., the substrate closest to the media, has a high index of refraction relative of fused silica, for which  $n=1.36$ . Preferably, this index is at least .3 greater than that of the substrate. One example candidate material, SF56A, has a refractive  
15 index of 1.785. If the bottom substrate is in very close proximity to the media, e.g., less than 0.5 microns, the use of a high index substrate allows a smaller spot size to be realized. The numerical aperture N.A. is defined by the following:

$$\text{N.A.} = n \sin \theta$$

where  $n$  is the refractive index of the image space and  $\theta$  is the half-angle of the  
20 maximum cone of light accepted by the lens. Thus, if the bottom substrate is in very close proximity to the media, the higher the index of refraction of the bottom

substrate, the smaller the acceptance half-angle for the same performance. This reduction in angle increases the efficiency of the system.

As shown in Figure 5, the slider block 61 in accordance with the present invention includes a die composed of a plurality of chips, each surface of which is  
5 available for imparting optical structures thereon. The die is formed from wafers having an array of respective optical elements formed thereon on either one or both surfaces thereof. The individual optical elements may be either diffractive, refractive or a hybrid thereof. Bonding material 25 is placed at strategic locations on either substrate in order to facilitate the attachment thereof. By surrounding the optical  
10 elements which are to form the final integrated die, the bonding material or adhesive 25 forms a seal between the wafers at these critical junctions. During dicing, the seal prevents dicing slurry from entering between the elements, which would result in contamination thereof. Since the elements remain bonded together, it is nearly impossible to remove any dicing slurry trapped there between. The dicing slurry  
15 presents even more problems when diffractive elements are being bonded, since the structures of diffractive elements tend to trap the slurry.

Advantageously, the wafers being bonded include fiducial marks somewhere thereon, most likely at an outer edge thereof, to ensure alignment of the wafers so that all the individual elements thereon are aligned simultaneously. Alternatively, the  
20 fiducial marks may be used to facilitate the alignment and creation of mechanical alignment features on the wafers. One or both of the fiducial marks and the alignment features may be used to align the wafers. The fiducial marks and/or alignment features

are also useful in registering and placing the active elements and any attendant structure, e.g., a metallic coil and contact pads therefor, on a bottom surface. These active elements could be integrated either before or after dicing the wafers.

On a bottom surface 67 of the slider block 61 in accordance with the present invention, a magnetic head 63 including thin film conductors and/or a magnetic coil is integrated using thin film techniques, as disclosed, for example, in U.S. Patent No. 5,314,596 to Shukovsky et al. Entitled "Process for Fabricating Magnetic Film Recording Head for use with a Magnetic Recording Media." The required contact pads for the magnetic coil are also preferably provided on this bottom surface.

Since the magnetic coil 63 is integrated on the bottom surface 67, and the light beam is to pass through the center of the magnetic coil, it is typically not practical to also provide optical structures on this bottom surface. This leaves the remaining five surfaces 50-58 available for modification in designing an optical system. Further, additional wafers also may be provided thereby providing a total of seven surfaces. With the examples shown in Figs. 2A and 3A the surface 50 would correspond to surface 20 or 40, respectively, the surface 52 would correspond to surface 22 or 32, respectively, the surface 54 would correspond to surface 24 or 34, respectively, and the surface 56 would correspond to surface 26 or 36, respectively.

Each of these wafer levels can be made very thin, for example, on the order of 125 microns, so up to four wafers could be used even under the most constrained conditions. If size and heat limitations permit, a light source could be integrated on the top of the slider block, rather than using the fiber for delivery of light thereto. In

addition to being thin, the use of the wafer scale assembly allows accurate alignment of numerous objects, thereby increasing the number of surfaces containing optical power, which can be used. This wafer scale assembly also allows use of passive alignment techniques. The other dimensions of the slider block 61 are determined by  
5 the size of the pads for the magnetic coil, which is typically 1500 microns, on the surface 67, which is going to be much larger than any of the optics on the remaining surfaces, and any size needed for stability of the slider block 61. The bottom surface 67 may also include etch features thereon which facilitate the sliding of the slider block 61.

10 Many configurations of optical surfaces may be incorporated into the slider block 61. The bonding, processing, and passive alignment of wafers is disclosed in co-pending, commonly assigned U. S. Application No. 08/727,837 entitled "Integrated Optical Head for Disk Drives and Method of Forming Same" and U. S. Application No. 08/943,274 entitled "Wafer Level Integration of Multiple Optical Heads" which  
15 are both hereby incorporated by reference in their entirety.

Additionally, an optical element can be provided on the bottom surface 67 of the bottom wafer as shown in Figure 6. When providing an optical element on this bottom surface 67, a transparent layer 65, having a different refractive index than that of the wafer itself is provided between the bottom surface 67 and the coil 63. The  
20 difference in refractive index between the layer 65 and the wafer should be at least approximately 0.3 in order to insure that the optical effect of the optical element provided on the bottom surface 67 is discernable. Also as shown in Figure 6, a single



wafer may be used if sufficient performance can be obtained from one or two optical elements.

Further as shown in Figure 6, metal portions 69 may be provided to serve as an aperture for the system. These apertures may be integrated on any of the wafer surfaces. The aperture may also serve as the aperture stop, typically somewhere in the optical system prior to the bottom surface thereof. When such metal portions 69 serving as an aperture are provided on the bottom surface 67, it is advantageous to insure the metal portions 69 do not interfere with the operation of the metal coil 63.

A problem that arises when using a system with a high numerical aperture for a very precise application is that the depth of focus of the system is very small. Therefore, the distance from the optical system to the media must be very precisely controlled to insure that the beam is focused at the appropriate position of the media. For the high numerical apertures noted above, the depth of focus is approximately 1 micron or less. The thicknesses of the wafers can be controlled to within approximately 1-5 microns, depending on the thickness and diameter of the wafer. The thinner and smaller the wafer, the better the control. When multiple wafers are used, the system is less sensitive to a variation from a design thickness for a particular wafer, since the power is distributed through all the elements.

When using multiple wafers, the actual thickness of each wafer can be measured and the spacing between the wafers can be adjusted to account for any deviation. The position of the fiber or source location can be adjusted to correct for thickness variations within the wafer assembly. Alternatively, the design of a



diffraction element may be altered in accordance with a measured thickness of the slider block in order to compensate for a variation from the desired thickness. Alternatively, the entire system may be designed to focus the light at a position deeper than the desired position assuming the thicknesses are precisely realized. Then, the layer 65 may be deposited to provide the remaining required thickness to deliver the spot at the desired position. The deposition of the layer 65 may be more precisely controlled than the formation of the wafers, and may be varied to account for any thickness variation within the system itself, i.e., the layer 65 does not have to be of uniform thickness. If no optical element is provided on the bottom surface 67, then the refractive index of the layer 65 does not need to be different from that of the wafer.

Figure 7 is a side view of another embodiment of the slider block. As shown in Figure 7, the fiber 8 is inserted into the top wafer and the mirror 9 is integrated into the top wafer, preferably at a 45-degree angle. Light reflected by the mirror 9 is directed to a diffraction element 71, followed by a refractive element 73, followed by a diffraction element 75, followed by a refractive element 77, and delivered through the coil 63. For such a configuration, the top surface 50 is no longer available for providing an optical element.

Additionally, for fine scanning control of the light, the mirror 9 may be replaced with a micro-electro-mechanical system (MEMS) mirror mounted on a substrate on top of the top chip. A tilt angle of the MEMS is controlled by application of a voltage on a surface on which the reflector is mounted, and is varied in

accordance with the desired scanning. The default position will preferably by 45 degrees so the configuration will be the same as providing the mirror 9.

An additional feature for monitoring the spot of light output from the slider block is shown in Figures 8A and 8B. As shown in Figure 8A, in addition to the optical system, consisting of, for example, diffractive elements 87, 89, used for delivering light through the magnetic coil 63, monitoring optical elements 81, 83 are provided. The monitoring optical elements 81, 83 are of the same design as the elements of the optical system 87, 89, respectively. In other words, the monitoring optical elements are designed to focus at a same distance as that of the optical system.

Advantageously, the monitoring optical elements 81, 83 are larger than the optical system elements for ease of construction and alignment of the test beam. In the configuration shown in Figures 8A and 8B, the monitoring optical elements 81, 83 are approximately twice the size of the element 87, 89. The monitoring system also includes an aperture 85, preferably formed by metal. It is noted that Figure 8B does not show the magnetic coil 63.

During testing, light is directed to the monitoring optical system to insure that light is being delivered to the aperture at the desired location. The magnitude of light passing through the aperture will indicate if the optical system is sufficiently accurate, i.e., that the light is sufficiently focused at the aperture to allow a predetermined amount of light through. If the light is not sufficiently focused, the aperture will block too much of the light.

Thus, by using the monitoring system shown in Figures 8A and 8B, the optical system of the slider block may be tested prior to its insertion into the remaining

device, even after being integrated with the active element 63. The dimension requirement imposed by the contact pads for the magnetic coil 63 and the coil itself result in sufficient room available on the wafers for the inclusion of such a monitoring system, so the size of the slider block is unaffected by the incorporation of the  
5 monitoring system.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following  
10 claims.

What is claimed:

- 1           1. An integrated micro-optical system comprising:  
2           a die formed from more than one wafer bonded together, each wafer having  
3           a top surface and a bottom surface, bonded wafers being diced to yield multiple  
4           dies; and  
5           an active element having a characteristic which changes in response to an  
6           applied field, integrated on a bottom surface of the die, optical elements being  
7           formed on more than one surface of said die.
- 1           2. The system of claim 1, wherein the active element comprises a thin film  
2           conductor whose magnetic properties changes when a current is applied thereto.
- 1           3. The system of claim 1, wherein said die is formed from two wafers and  
2           optical elements are formed on a top surface and a bottom surface of a top wafer  
3           and a top surface of the bottom wafer.
- 1           4. The system of claim 1, wherein said die includes a high numerical  
2           aperture optical system.
- 1           5. The system of claim 1, wherein a bottom wafer of said more than one  
2           wafer has a higher index of refraction than other wafers.
- 1           6. The system of claim 1, wherein there are no optical elements on a  
2           bottom wafer of the die.

1           7. The system of claim 1, wherein the bottom surface of the die further  
2 comprises features for facilitating sliding of the integrated micro-optical system  
3 etched thereon.

1           8. The system of claim 1, wherein metal portions serving as apertures are  
2 integrated on at least on one said surfaces of said die.

1           9. The system of claim 1, further comprising a layer of material deposited  
2 on the bottom surface of the bottom wafer before the active element is integrated  
3 thereon.

1           10. The system of claim 9, further comprising an optical element formed  
2 on the bottom surface of the bottom wafer, wherein the layer has a refractive index  
3 that is different from a refractive index of the bottom wafer.

1           11. The system of claim 9, wherein the layer is deposited in accordance  
2 with a difference between a desired thickness and a measured thickness.

1           12. The system of claim 1, further comprising a monitoring optical system  
2 formed on each surface of said wafer containing an optical element.

1           13. The system of claim 1, further comprising means for varying a spacing  
2 between wafers in accordance with a difference between a measured thickness of  
3 a wafer and a desired thickness of a wafer.

1           14. The system of claim 1, wherein the active element is integrated as an  
2   array of active elements on the bottom wafer before the bonded wafers are diced.

1           15. The system of claim 1, wherein a top surface of the die is etched and  
2   coated with a reflective coating to direct light onto the optical elements.

1           16. The system of claim 1, further comprising a further substrate mounted  
2   on top of the top of the die having a MEMS mirror thereon.

1           17. The system of claim 1, further comprising an insertion point on the die  
2   for receiving an optical fiber therein.

1           18. The system of claim 17, wherein the insertion point is on a side of the  
2   die and the system further comprises a reflector for redirecting light output by the  
3   fiber.

1           19. The system of claim 1, wherein a bottom wafer of the die has a  
2   refractive element formed in a material of high numerical aperture.

1           20. The system of claim 19, wherein the refractive element is a spherical  
2   lens and the die further comprises a compensating element which compensates for  
3   aberrations exhibited by the spherical lens.

1           21. The system of claim 20, wherein the compensating element is on a  
2   surface immediately adjacent the spherical lens.

1           22. The system of claim 20, wherein the compensating element is a  
2   diffractive element.

1           23. The system of claim 19, wherein the refractive element is an aspheric  
2   lens.

1           24. The system of claim 19, wherein the die includes at least one additional  
2   refractive element, all refractive elements of the die being formed in material  
3   having a high numerical aperture.

1           25. An integrated micro-optical apparatus comprising a die formed from  
2   more than one wafer bonded together, each wafer having a top surface and a  
3   bottom surface, bonded wafers being diced to yield multiple die, at least two  
4   optical elements being formed on respective surfaces of each die, at least one of  
5   said at least two optical elements being a refractive element, a resulting optical  
6   system of each die having a high numerical aperture.

1           26. The integrated micro-optical apparatus of claim 25, wherein the  
2   refractive element is a spherical lens and the die further comprises a compensating  
3   element which compensates for aberrations exhibited by the spherical lens.

1           27. The integrated micro-optical apparatus of claim 26, wherein the  
2   compensating element is on a surface immediately adjacent the spherical lens.



1           28. The integrated micro-optical apparatus of claim 26, wherein the  
2   compensating element is a diffractive element.

1           29. The integrated micro-optical apparatus of claim 25, wherein the  
2   refractive element is an aspheric lens.

1           30. The integrated micro-optical apparatus of claim 25, wherein the die  
2   includes at least one additional refractive element, all refractive elements of the  
3   die being formed in material having a high numerical aperture.

1           31. The integrated micro-optical apparatus of claim 25, wherein the  
2   refractive element is on a bottom wafer and is of a material having a higher  
3   refractive index than that of the bottom wafer.

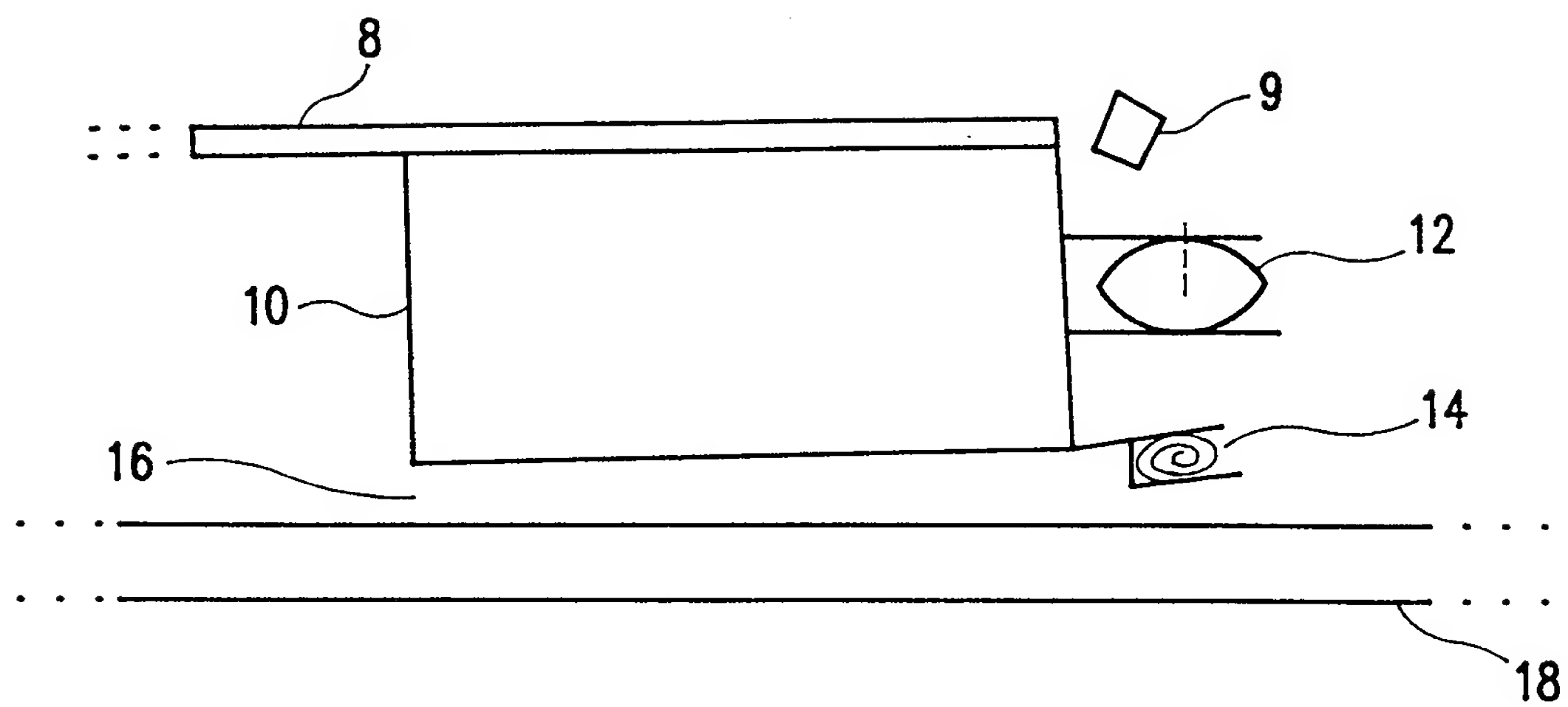
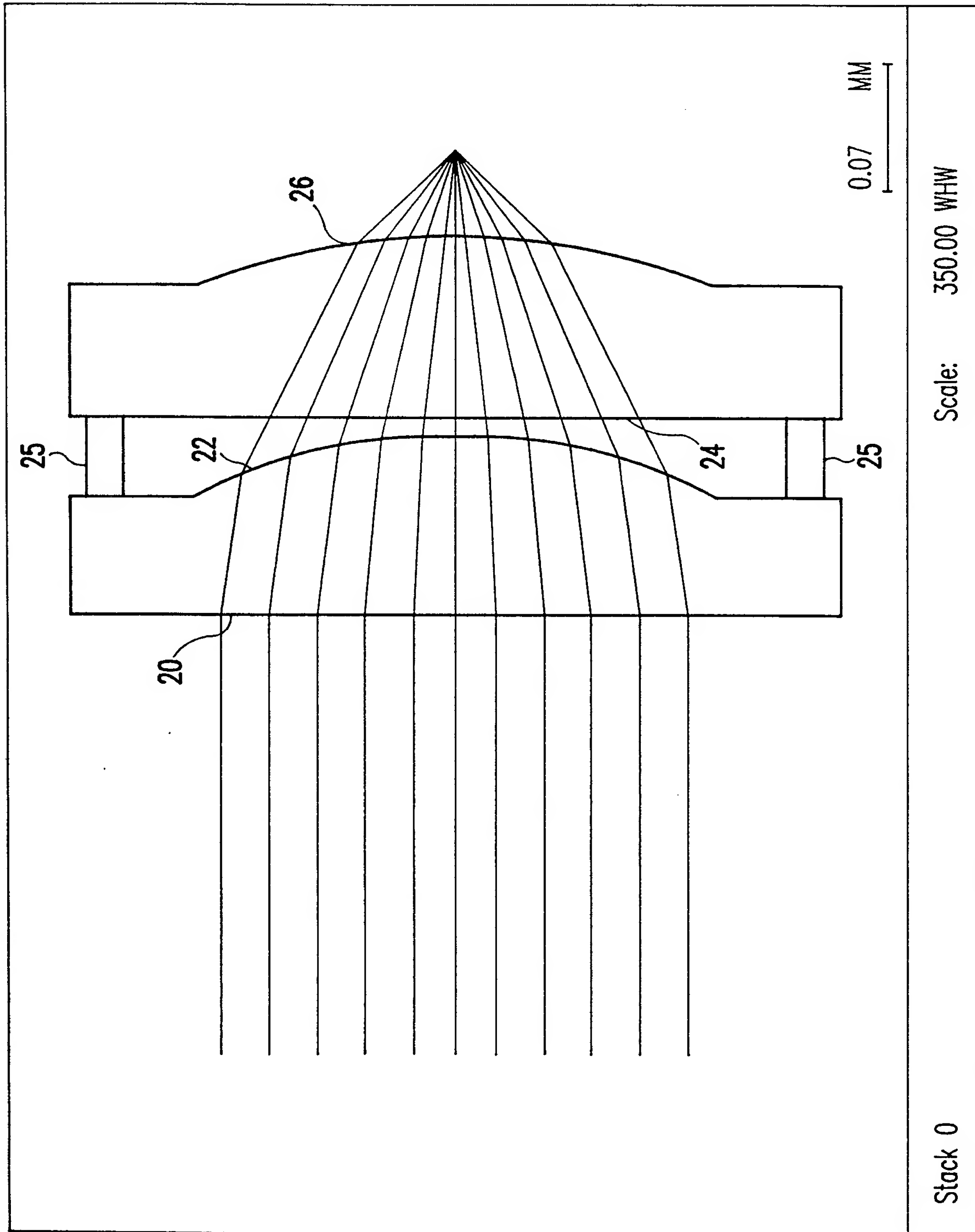
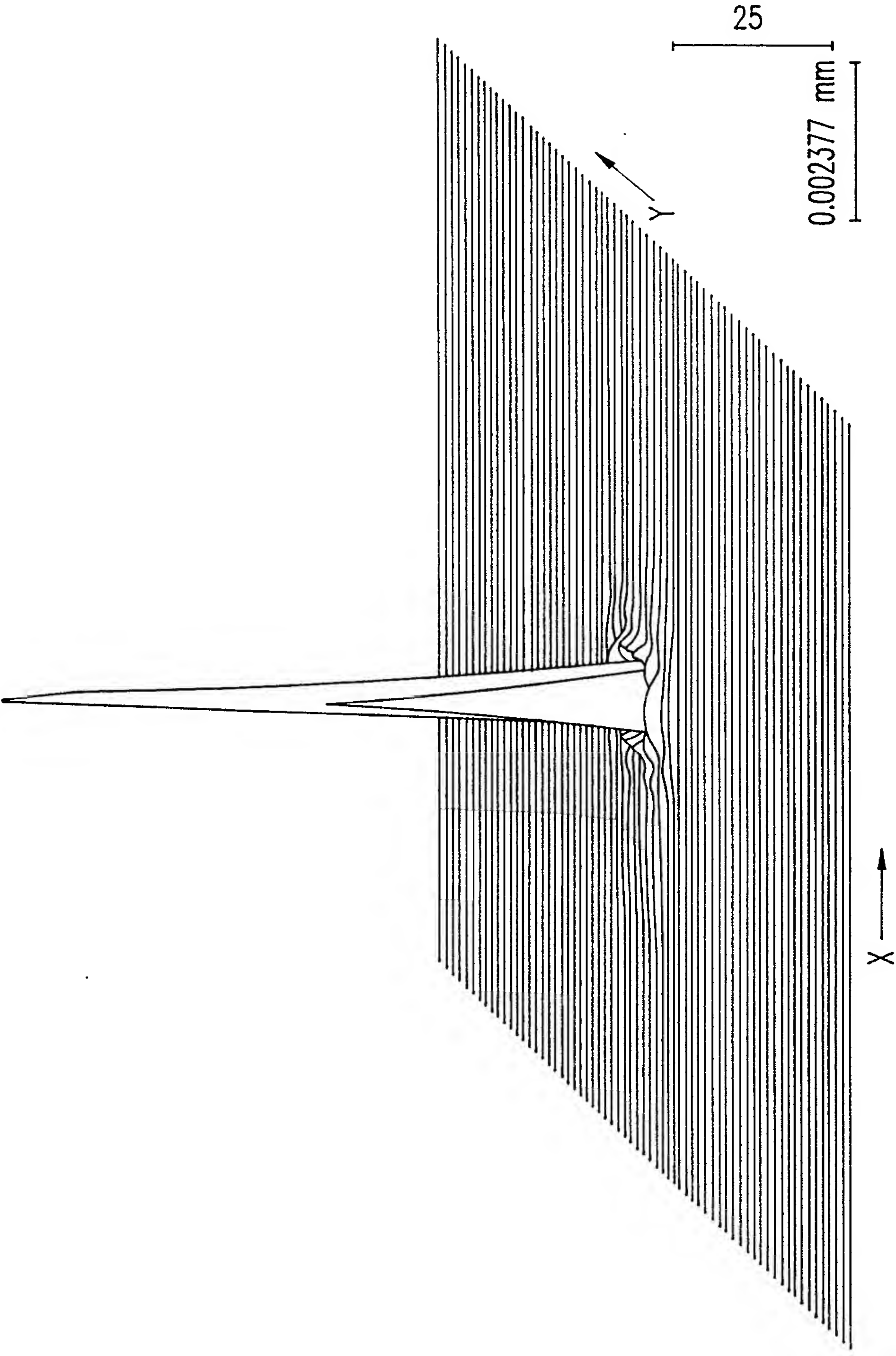


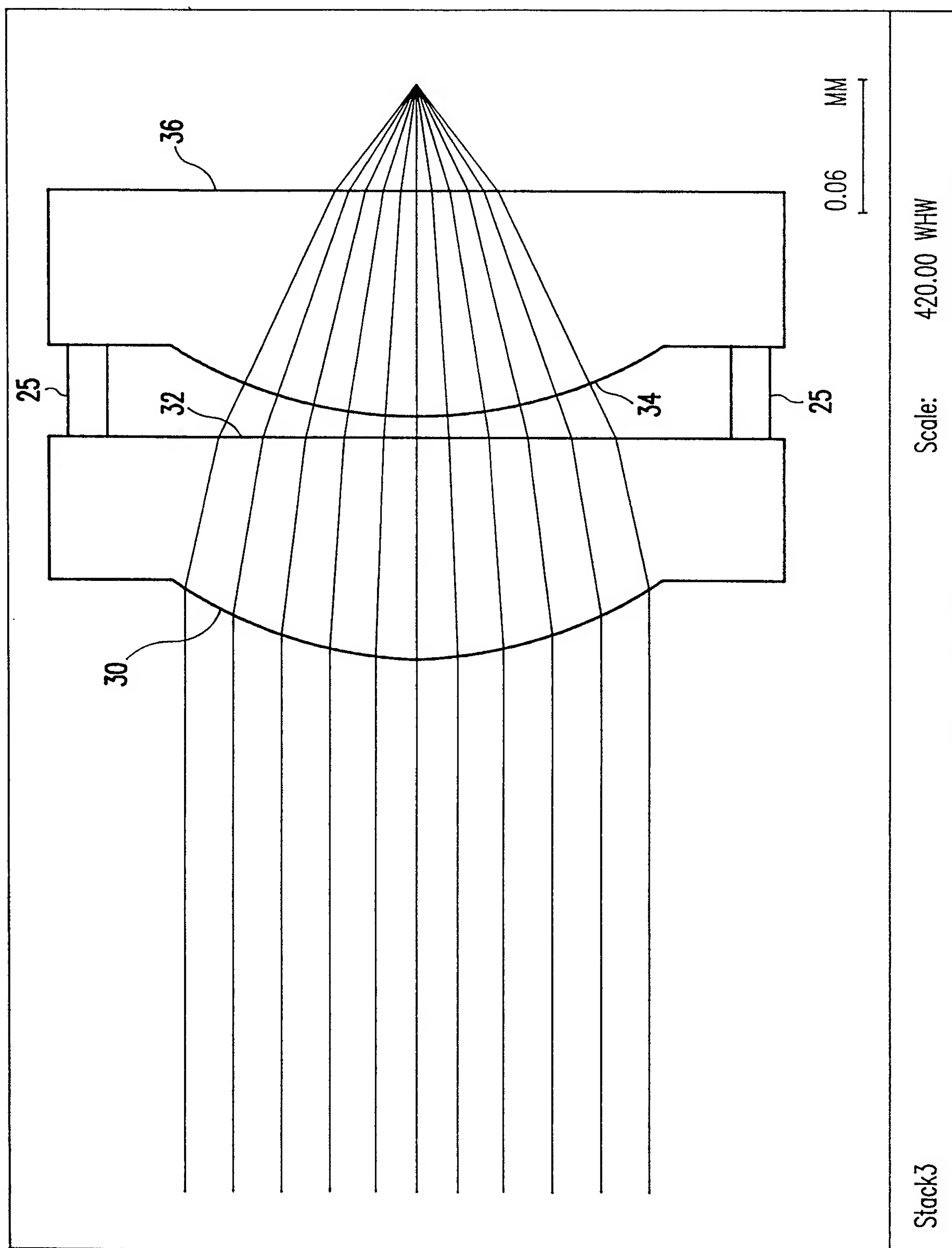
FIG. 1

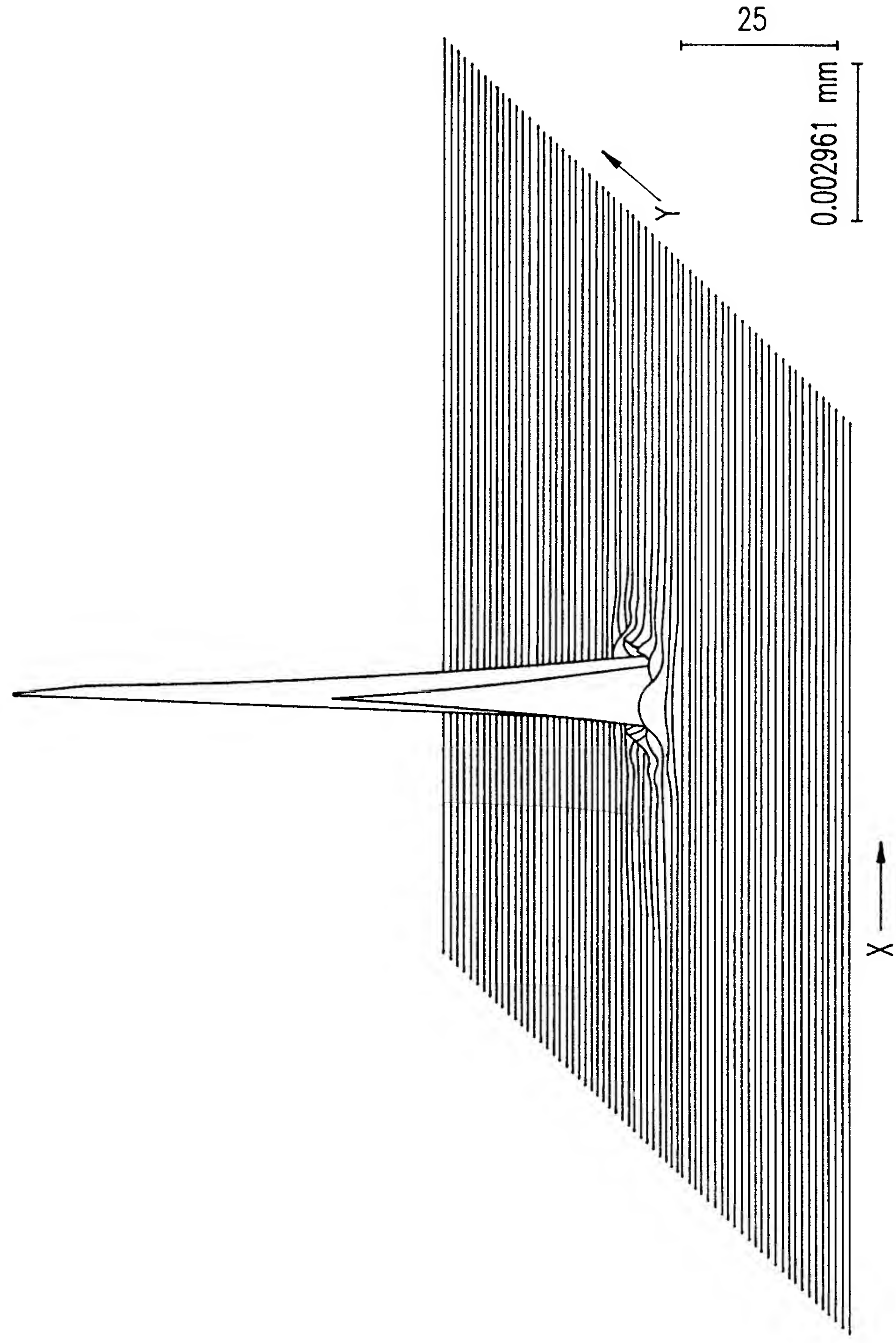




Stack0	DIFFRACTION INTENSITY SPREAD FUNCTION  FLD ( 0.00, 0.00)MAX ; (0.0, 0.0)DEG DEFOCUSING: 0.000000MM	WAVELENGTH WEIGHT 660.0 NM 1
POSITION 1		
WHW		

FIG. 2B





Stack3	DIFFRACTION INTENSITY SPREAD FUNCTION  FLD ( 0.00, 0.00)MAX ; (0.0, 0.0)DEG DEFOCUSING: 0.000000MM	WAVELENGTH	WEIGHT
POSITION 1		660.0 NM	1
WHW			

FIG. 3B

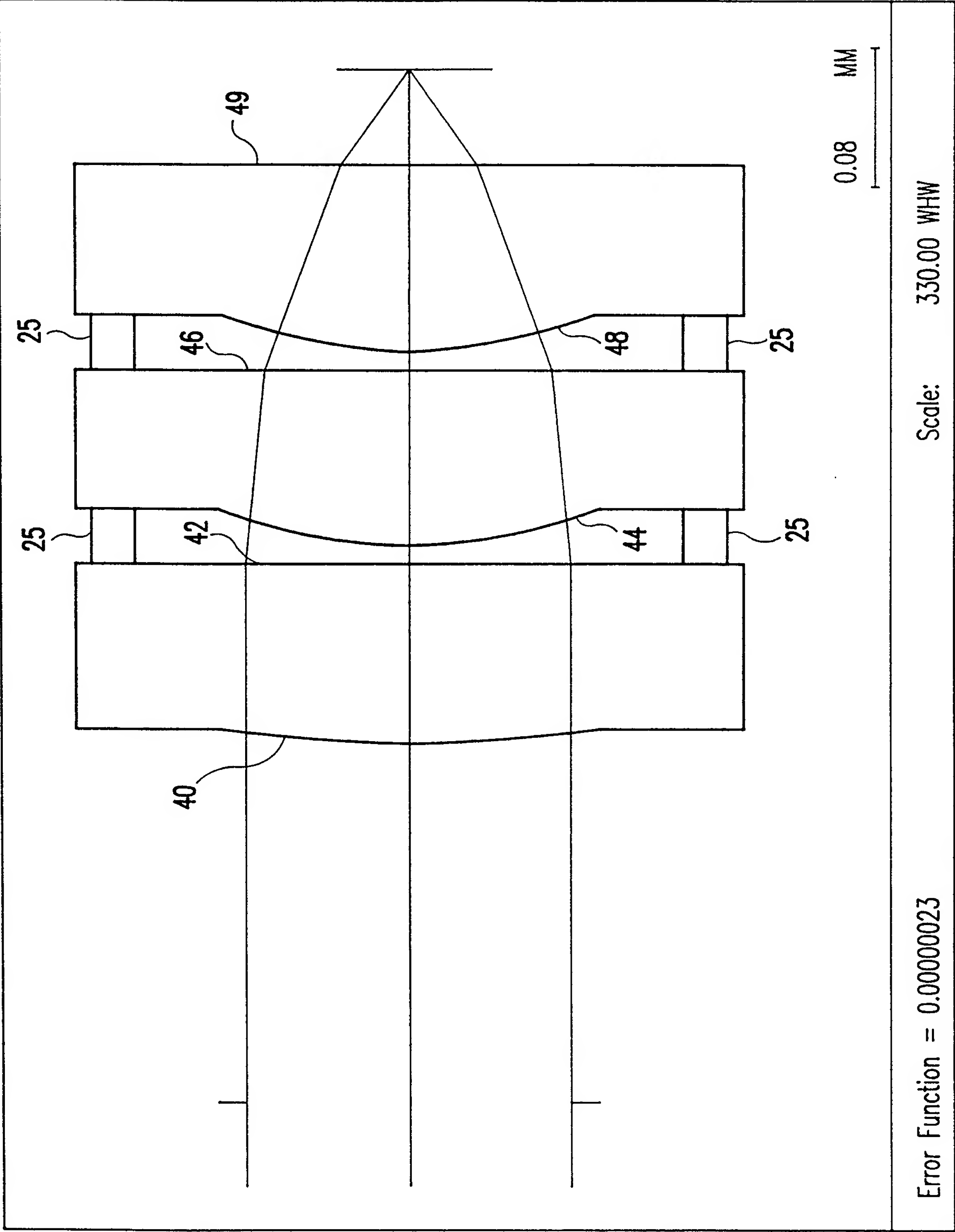
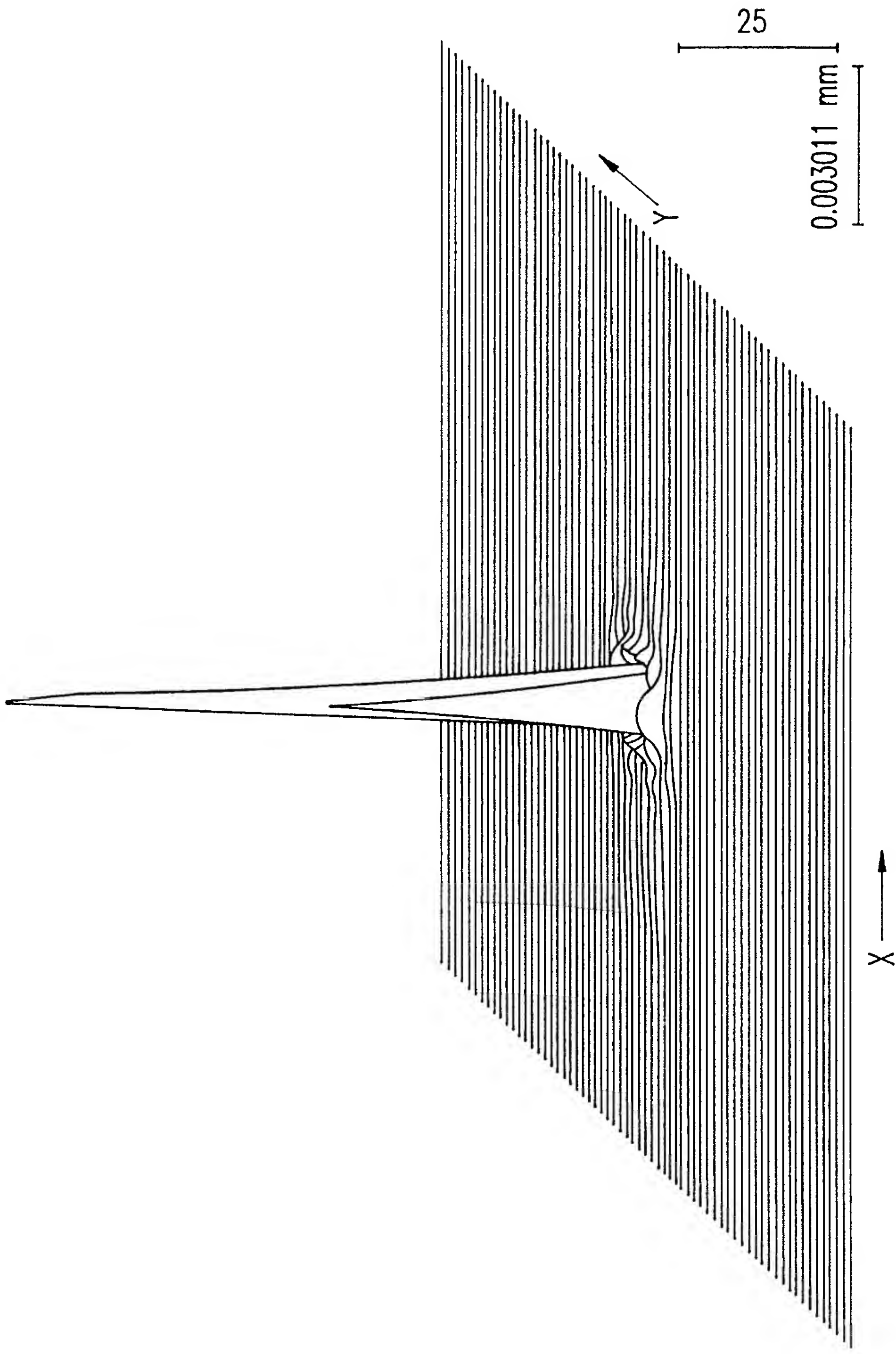


FIG. 4A





Stack3	DIFFRACTION INTENSITY SPREAD FUNCTION	WAVELENGTH WEIGHT
POSITION 1	FLD ( 0.00, 0.00)MAX ; (0.0, 0.0)DEG	660.0 NM 1
WHW	DEFOCUSING: 0.000000MM	

FIG. 4B

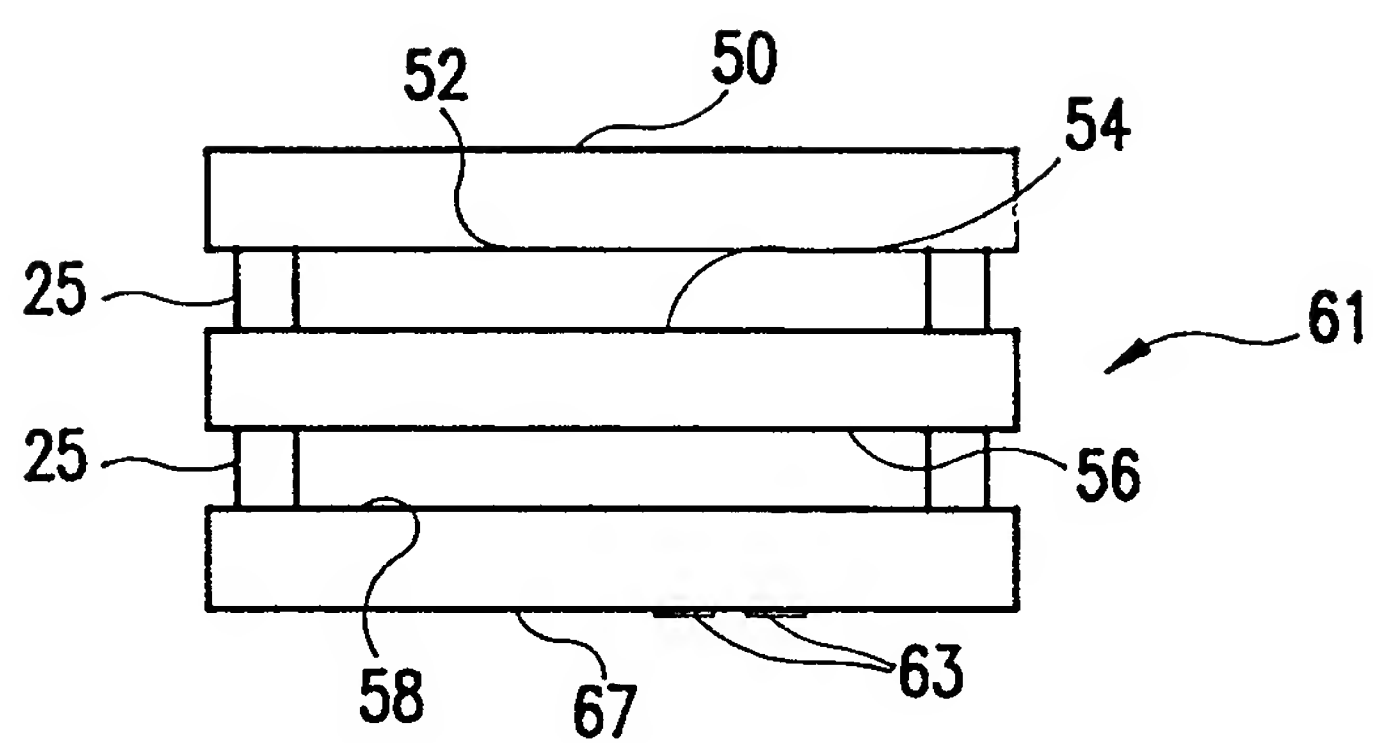


FIG. 5

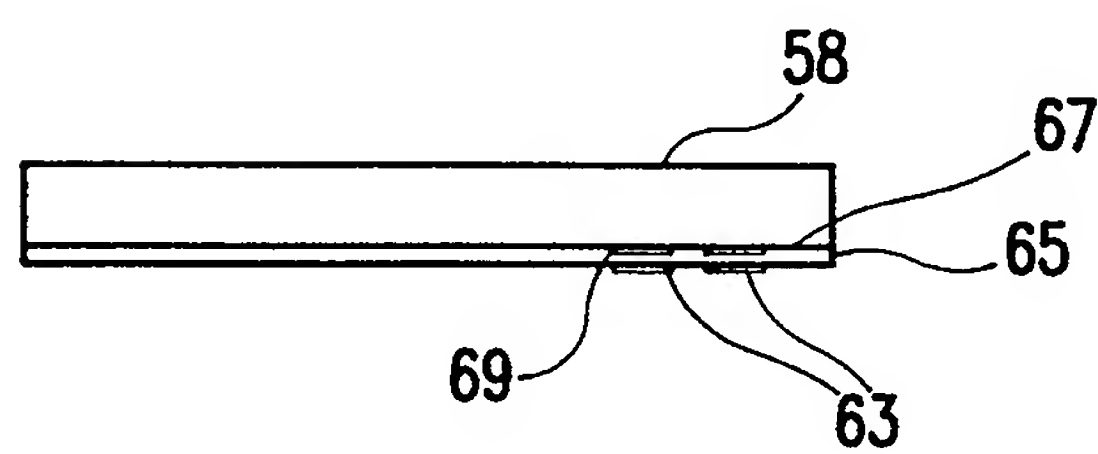


FIG. 6

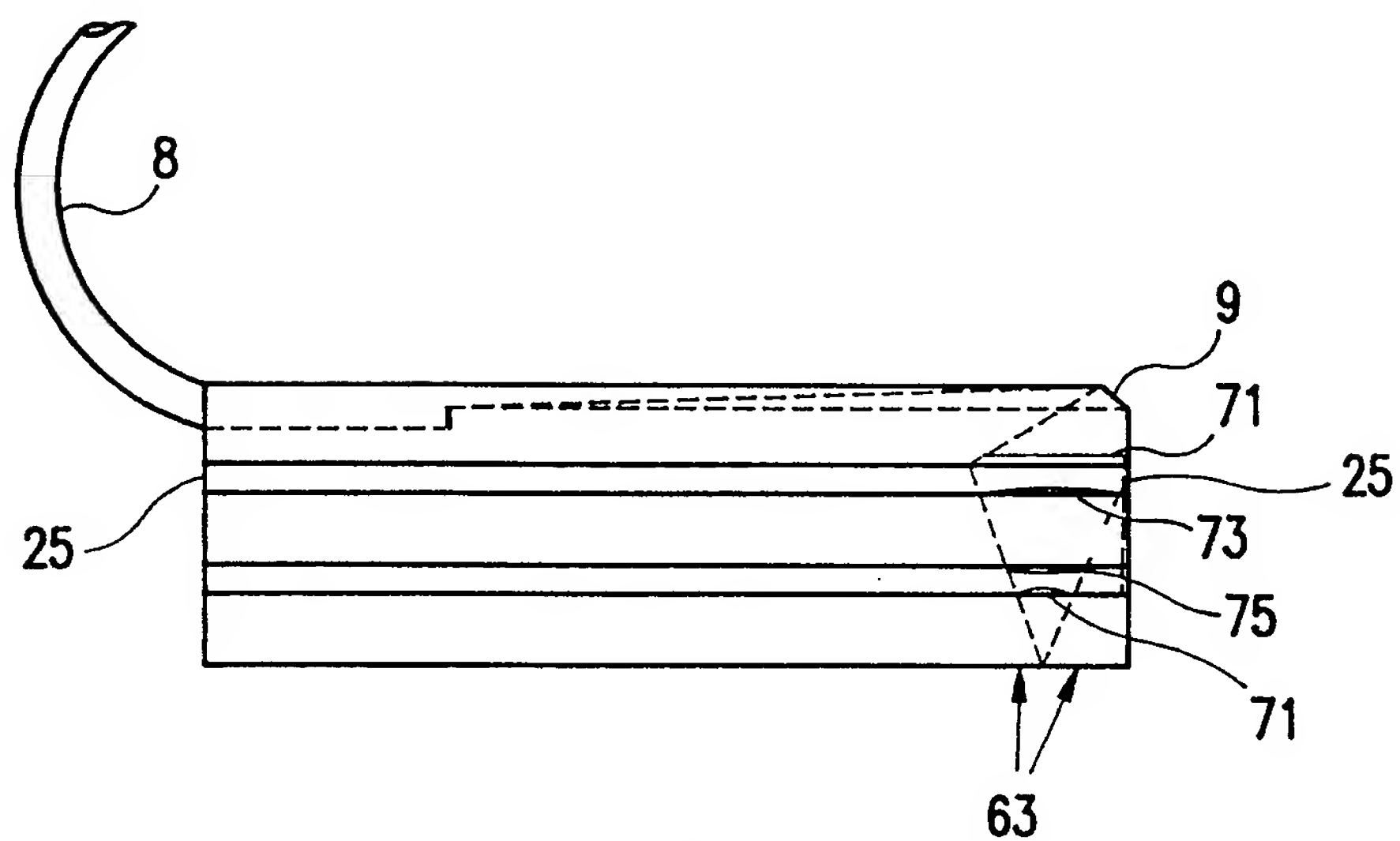


FIG. 7

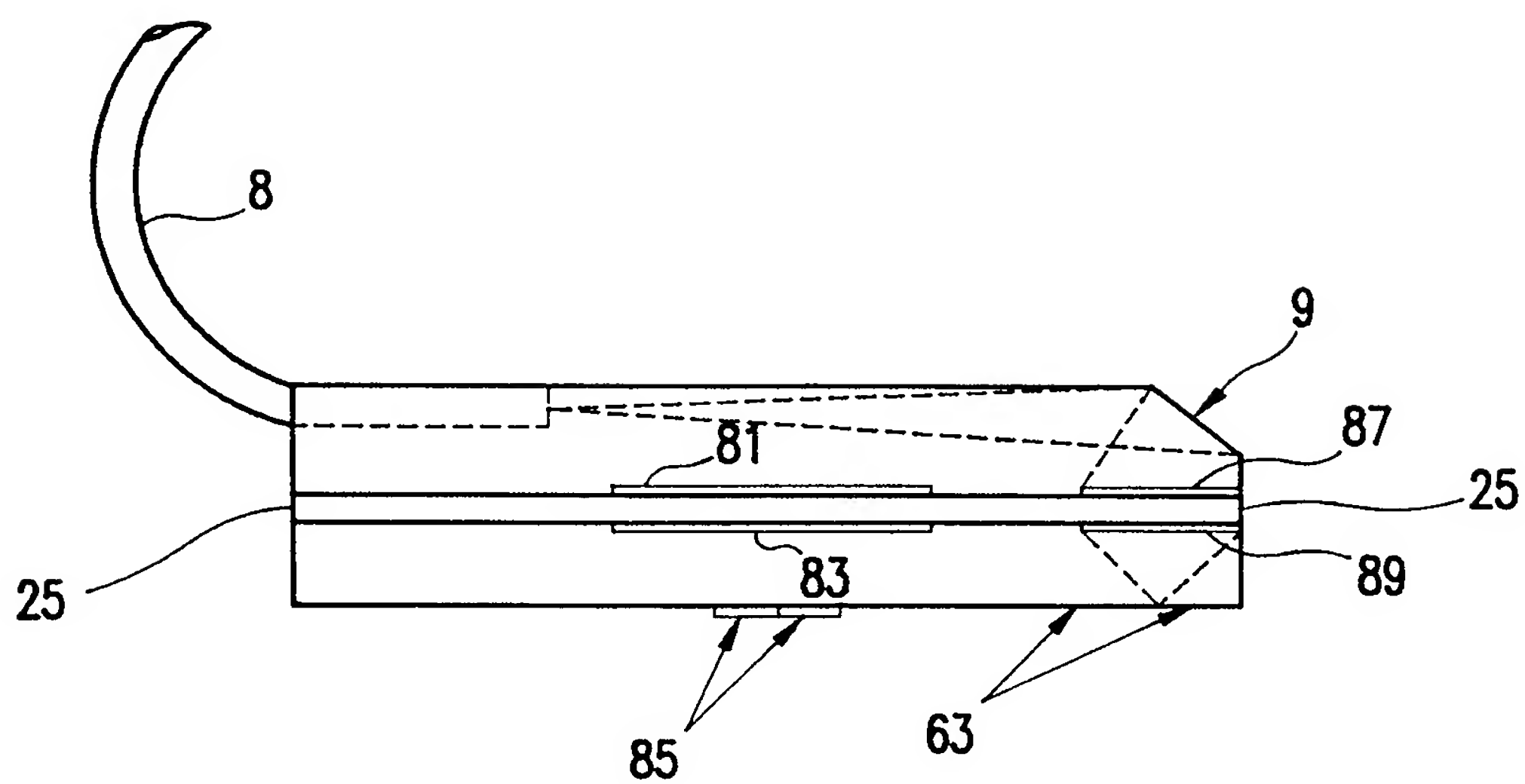


FIG. 8A

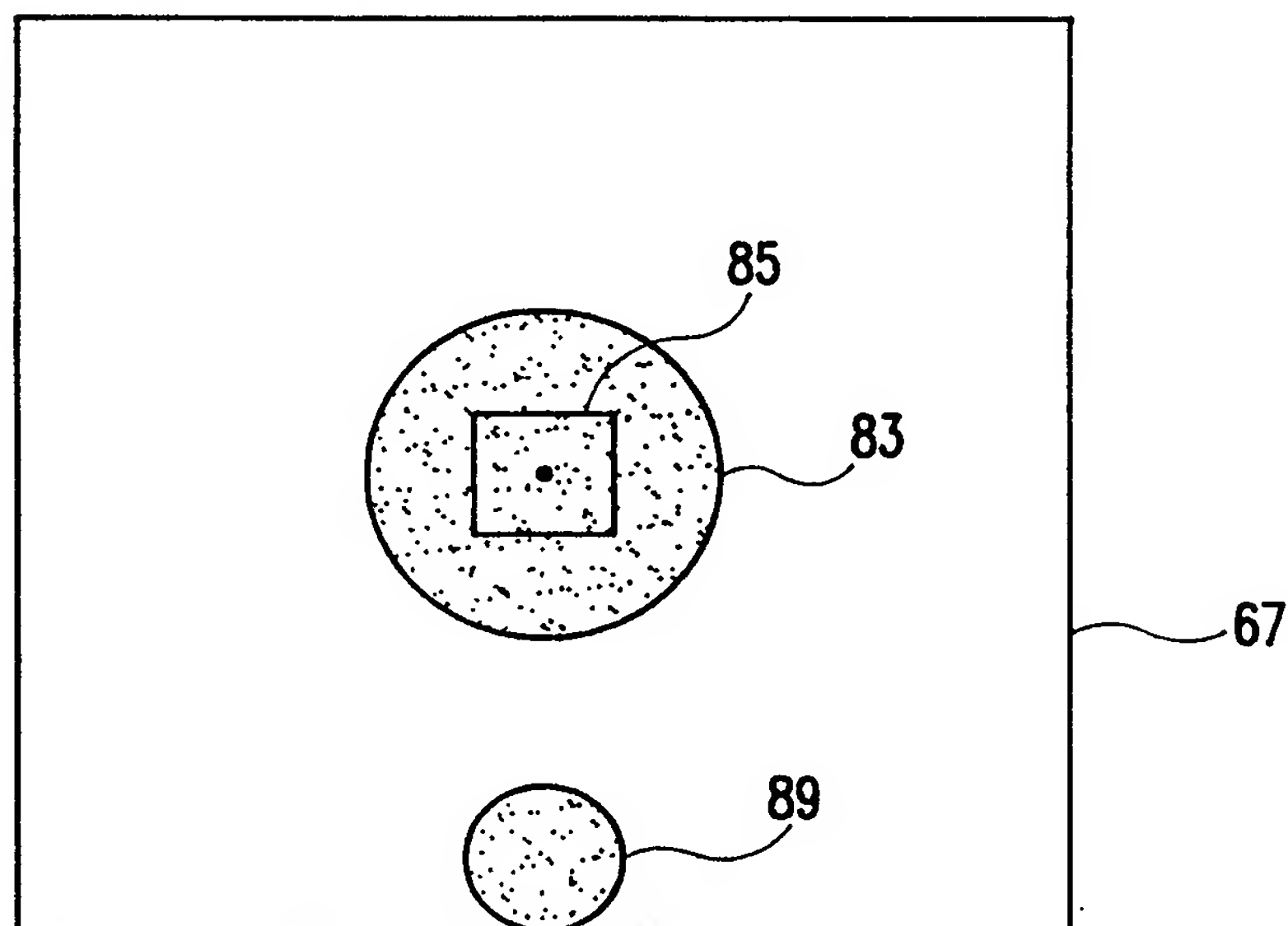


FIG. 8B